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Effective Use of USDA-ARS Experimental Watersheds

D.C. Goodrich[1], P. Starks[2], R.R. Schnabel[3], D.D. Bosch[4]

Summary

The geographically distributed experimental watersheds operated by the USDA-Agricultural Research Service (ARS) constitute one the best networks of its kind in the world. The watersheds are, and continue to be a national treasure of hydrologic knowledge and history. However, changing demands and monetary constraints require a critical re-examination of the ARS Experimental Watershed Research Program mission to ensure effective utilization, maintenance and continued improvement of this precious resource. To set the stage for this endeavor, a historical perspective of ARS watershed establishment is presented. Critical gaps within the current watershed network are examined and significant research opportunities which build upon, and enhance the status and capabilities of the ARS Experimental Watersheds are discussed. Finally, crucial decisions must be made to define the appropriate role of ARS experimental watersheds and level of data collection within them to address new and emerging agricultural and societal needs under strict budgetary constraints.

Introduction

> *"The collection of basic data is an attribute of intelligent sovereignty; a wise sovereign seeks to know the value as well as the extent of its domain." (Langbein 1965)*

Langbein (1965) went on to define the concept of a network for collection of basic hydrologic data. "Its component parts must be related to one another, that is, each station, point, or region of observation must fill one or more definite niches in either space or time." While Langbien's focus was on national networks, Neff (1965) more thoroughly discussed the local network, which embodies the philosophy of network design for individual ARS experimental watersheds. In a local, intensive network more precise, quantitative data is collected for specific hydrologic interpretations. This is in contrast to a national, or extensive network which collects qualitative information for broad interpretation by providing regional "index" information. Significant scientific attention was given to the establishment of hydrologic networks and representative and experimental areas during the International Hydrologic Decade (Tison 1965a and 1965b). By the time of these publications (Tison 1965a and 1965b), the ARS and its predecessors already had a relatively long and impressive history of intensive, local network, hydrologic data collection.

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[1] Research Hydraulic Engineer, USDA-ARS, 2000 E. Allen Rd., Tucson, AZ 85719
[2] Soil Scientist, USDA-ARS, 7207 W. Cheyanne St., El Reno, OK 73036
[3] Soil Scientist, USDA-ARS, Curtain Road, University Park, PA 16802
[4] Research Hydraulic Engineer, USDA-ARS, P. O. Box 946, Tifton, GA 31793

The ARS Experimental Watershed Program grew out of early, depression era efforts by the Civil Conservation Corps (CCC) and the Soil Conservation Service (SCS). Kelly and Glymph (1965) provide a description of the early history of the watershed program as we know it today. They begin by describing early research associated with the 1930's conservation motto of "stop the water where it falls." The research focused on the merits of upstream watershed conservation to hold the water and to reduce runoff and erosion. This research was geared to studying on-site problems and concentrated on field-sized watersheds up to roughly 10 hectares and, to a large extent, utilized paired watershed analyses. In 1935, major research stations were established in Coshocton, OH, Hasting, NE, and Riesel, TX to examine fields and watersheds up to several hundred hectares (square kilometers) in size. Research still concentrated on on-site effects of tillage and management practices, but plot and lysimeter studies were incorporated. Kelly and Glymph (1965) describe the research during this period as largely empirical with emphasis on accurate data collection. In the 1950's, emphasis moved to a larger scale, and national programs were developed for controlling flood waters and sediment, as well as assessing downstream effects on watersheds up to 1,000 km^2. Many of the experimental watersheds were transferred to the newly formed USDA-ARS in 1954.

There was early recognition of the scaling problems in transferring knowledge from data collected at the small scale to larger watersheds (Harrold and Stephens 1965). This problem and growing concern of downstream, off-site impacts of upstream watershed practices resulted in the establishment of a subset of larger ARS experimental watersheds associated with new watershed research centers in a number of hydroclimatic regions in compliance with U.S. Senate Document 59 (Great Plains, Northeast, Northwest, Southeast, and Southwest Watershed Research Centers in Chickasha, OK; State College, PA; Boise, ID; Tifton, GA; and Tucson, AZ; respectively). The goal of the watershed research centers was to select a representative basin and establish satellite basins, that were less well instrumented, to extend the data and findings from the primary watershed center. Nested watersheds and unit source areas on major soil types were included in the watershed designs to investigate scale effects.

A recent overview of ARS experimental watershed research is given in DeCoursey (1992). A description of data acquisition programs and an assessment of the quality of collected data at many of the experimental watersheds is also described in Johnson et al. (1982). Based on data from the Hydrology Laboratory in Beltsville, Maryland, as of Jan. 1, 1991, ARS has operated over 600 watersheds in its history. Of the 600 watersheds, a comprehensive database is available from the Hydrology Laboratory for 333 of these watersheds. Currently, 140 watersheds are active and collecting a variety of data. Table 1, reproduced from DeCoursey (1992), describes the size distribution, length of record and primary land use of the active watersheds. The geographic location of both active and closed watersheds is illustrated in Figure 1 (as of Jan. 1, 1992). In many of the locations depicted on this figure, multiple watersheds exist or have existed. In general, active watersheds are still well distributed over the contiguous 48 United States.

Early experimental watershed research needs were largely oriented to solving pressing field problems. In 1965, Hikok and Ree (1965) stated that the objectives of ARS and its predecessors were: "...1) accumulation of basic-rainfall-runoff data, primarily for design of soil and water conservation structures; 2) study of the effects of land-use and treatment practices on the runoff and sediment production from upstream watershed source areas; and 3) evaluation of overall effects of watershed management and protection programs on flood expectancies, and net water and sediment yield of larger, complex watersheds." Additional objectives were also more formally defined by annual SCS research needs statements (Kelly and Glymph 1965). Since then, these research objectives have changed and evolved to address current problems such as chemical water quality and climate change in addition to improving our understanding of basic hydrology and soil-water-plant relationships.

In a 1991 report, the National Research Council (1991) noted that water resource applications have often preceded science. For example, those in applied professions such as Civil and Agricultural Engineering are credited as being largely responsible for water-related health and safety enjoyed by modern society. In a parallel vein, the establishment of ARS experimental watersheds was largely justified on grounds of on- and off-site impacts related to management and human applications. This does not imply that improved scientific understanding was not a goal of early ARS experimental watershed research (Holtan and Whelan 1965, Harrold and Stephens 1965, Kelly and Glymph 1965, and Holtan 1970), but that establishment and watershed funding was primarily driven by water resource applications and associated impacts. However, with current concerns of potential global change impacts, a realization has come forth for an improved, multidisciplinary understanding of the coupled water, energy and biogeochemical cycle over a wide range of temporal and spatial scales. The National Research Council (1991) concluded that to meet this challenge, a more scientific, less applications oriented approach must be utilized. The critical role of experimental watershed data in this quest for scientific understanding was reiterated as they stated, "The needed understanding will be built from coordinated, long-term data sets (both at fine and large spatial scales) and founded on an educational base in the geosciences." (National Research Council 1991). The scientific strength of ARS and its Experimental Watershed Program place it in a strategic position to take up this challenge.

Scientific Challenges

The ARS experimental watersheds must play an integral role in meeting the challenge of addressing societal needs for agricultural production and environmental protection under non-stationary global climatic conditions. Complex computer models have been, and are being developed, to address these needs. However, confidence in computer models and their simulations can only be acquired via verification with observations. It must be recognized that in many cases the complexity of computer models far exceeds our ability to economically collect data to parameterize and verify these models. To meet this challenge, a variety of critical gaps which exist in the ARS experimental watershed data collection and associated database organization must be addressed. In the current budgetary climate, this will force re-examination and prioritization of watershed objectives as well as necessitate closer interagency cooperation. We must reevaluate how the long term records are being used and ask ourselves several critical questions. Are we collecting the correct information, or are we collecting data for data's sake? Are we collecting data that does not aid or help us address our research objectives? Are we operating at the proper spatial and temporal scales? Are there additional types of data that we need to collect?

Critical Measurement or Information Gaps

Due to changing research needs and objectives, auxiliary measurements, not envisioned by those who established the experimental watersheds, are required. A list of critical measurements and/or information gaps that exists at many, and in some cases, all of the ARS experimental watersheds is contained in Table

2. Local conditions would of course modify needs and methods for each of the items contained in this table.

To better understand land-atmosphere interactions and the water balance itself, it is essential that we monitor the energy balance. It is no longer sufficient to treat evapotranspiration as a residual in the water balance. Longer term water quality and primary nutrient records are required at the watershed scale to both establish trends and study management effects. Because the transport dynamics and residence times of streams and lakes are vastly different than field-scale dynamics, temporal records of greater length are required to track contaminants once they are transported out of the field. In addition to longer duration, the temporal sampling of water quality measurements must be frequent enough to characterize individual storm effects. The spatial sampling scale must also be small enough to evaluate causal relationships. The suite of measurements taken by the USGS National Water Quality Assessment Program could provide a model for the ARS experimental watershed program to initially evaluate.

To organize spatially distributed experimental watershed data and characteristics it is essential to develop high quality GIS coverage layers for the basin characteristics listed in Table 2. This need will become more evident in the application and testing of more complex, multi-dimensional large area hydrology models (also see Arnold et al., this issue). To further large area hydrologic applications it is essential to acquire remotely sensed data over the experimental watersheds. Due to both the data collection density and length of record it is likely that ARS experimental watersheds will be excellent locations to test methodologies and model strategies which directly utilize remotely sensed data. To more fully understand the long term implications of climate change, the ability to model feedback mechanisms between the biosphere, atmosphere and hydrosphere must be developed. This necessitates ecological and biomass characterization on ARS experimental watersheds. Similarly, to better understand and model nutrient cycling and water quality, biogeochemical balance measurements must be conducted. To a large degree, the ability to implement complex hydrologic models has exceeded the ability to verify these models with current measurements. Spatially distributed models must be verified with distributed observations, nested within the catchments being modelled. Without collecting this data it is not possible to draw conclusions regarding the within-catchment behavior of a models. These measurements will also be needed to go beyond one-dimensional modeling. To realistically identify possible long term climatic trends in a highly variable hydrometeorologic environment we must attempt to extend experimental watershed records back beyond the modern day record. Finally, to properly interpret both our historical database and future measurements, auxiliary, or metadata, information about the measurements must be compiled. Metadata, or "data about data", describing instrumentation, estimates of uncertainty and conditions which affect our measurements such as basin land use and management practices is essential for inter-watershed comparison and historical data interpretation. Computer compilation of historical metadata will become even more important as the scientists who established ARS Experimental Watersheds retire.

Limitations

At many ARS watersheds, an excellent job is done collecting some of the measurements listed in Table 2. From a budgetary standpoint, any one watershed location may not be able to collect all the information contained in the table. Budgetary considerations for instrumentation are one obvious limitation. An additional consideration that cannot be ignored is the necessity for trained personnel to make the measurements and interpret the data. Expertise to make many of the measurements listed in Table 2 is not widely available among the ARS experimental watershed/hydrology personnel. However, to tackle some of the national research problems related to water quality and global change facing the ARS, additional measurements will be required. If all the measurements at all the watersheds cannot be made, a subset of watersheds must be identified with a prioritized list of those measurements that will enable interregional watershed comparisons and continental assessments.

A second limitation is the size of the ARS experimental watersheds. It is very unlikely that current watersheds will be expanded with a level of instrumentation density that currently exists. This will limit the possibility of scaling up to and coupling with mesoscale meteorologic models and beyond to global climate models (GCM). ARS cannot realistically instrument and analyze all watershed scales and the proper scale(s) which would best meet present and future ARS objectives must be determined. Where does the scope of ARS inquiry begin and end? This must be resolved and should be closely tied to ARS objectives. To conduct large area analysis beyond ARS watershed scales will require utilization of data collected by other agencies such as National Weather Service (NEXRAD radar-rainfall estimates), USGS, NASA, and others. In turn, many of these agencies have, and will, look to ARS for high quality ground truth data and support measurements.

Deficiencies in our Underlying Scientific Knowledge

The problems associated with hydrologic spatial heterogeneity and cost efficient methodologies to measure it over large areas will continue to challenge the ARS Experimental Watershed Program (Bosch et al., this issue). Simple, cost effective instrumentation and methods to measure a variety of variables (i.e. soil hydraulic properties, soil moisture, erosion, deposition and sediment transport rates, water quality, hillslope distributions of overland flow velocity and depth, expanding and contracting areas of saturation, contributions to and from groundwater, etc) are still elusive for many of the variables mentioned.

For many measurements the principle of uncertainty will compromise measurement of other important watershed response variables. For example, from a geomorphic perspective, building a runoff measuring structure does not allow natural channel degradation, disrupts the gradeline and severely interferes with sediment transport. Due to measurement difficulty, some of the most significant watershed knowledge deficiencies arise in the subsurface environment. Knowledge of processes below the root zone and above the water table; surface water-groundwater interactions; travel time through the subsurface environment; and of simple methods for aquifer characterization, wetlands delineation and subsurface stratigraphy are scant in comparison to knowledge of surface processes.

The importance of an experimental watershed program like the one operated by ARS is underscored by the fact that other agencies are initiating similar programs. The U.S. Geological Survey has initiated a similar program, although on a much smaller scale with a slightly different focus. The Water, Energy, and Biogeochemical Balance (WEBB) program has begun establishing a number of small research watershed sites over a range of hydroclimatic zones (Kelmelis 1993). Additionally, the National Science Foundation Long Term Ecological Research (LTER) program (National Research Council 1991) also has sites in a variety of hydroclimatic regions with focus on interdisciplinary ecological research. ARS, with its established watersheds and long hydrologic records, is well positioned to provide more immediate answers to pressing issues than are newly established programs. However, to be successful ARS must avail itself to the opportunities to retrofit watersheds to obtain additional critical data.

Information Base

One class of experimental watershed database exists at individual ARS watershed locations and another at the ARS Water Data Center at the Beltsville Hydrology Laboratory. In addition to the long term rainfall-runoff data collected and forwarded to the Water Data Center, the individual locations often have additional extensive data sets. These include short-term, project oriented special collections, water quality and sediment data, GIS and remotely sensed data and historical descriptive information (metadata). Much of this data is not in computer compatible format and is in danger of being lost.

The combined ARS database formed by linkage of the individual experimental watersheds through central data deposition and organization by the ARS Water Data Center truly constitutes a "national network" of intensive watersheds in the spirit of Langbein's (1965) discussion. Efforts must be made to submit and pull in the additional data sets at the individual experimental watersheds. For the special MONSOON '90 multi-disciplinary field campaign (Kustas et al. 1991) on the Walnut Gulch Experimental Watershed, a special project data set is being assembled at the Water Data Center. To accomplish this for ongoing projects and to pull in the types of data listed above that are not normally submitted, the Water Data Center will require extra resources.

Another critical issue that the ARS must face is quality control for experimental watershed data. A U.S. Dept. of Agriculture (Johnson et al. 1982) report documents results of a survey to identify the key instrumentation and data quality concerns of the ARS research program. Reports of the survey were obtained from each data collection center but no formal recommendations or uniform quality control guidelines were established. In the opinion of Dr. Ken Renard (personal communication 1993) overall agency quality control of experimental data is virtually non-existent. It is assumed that each watershed established its data collection and instrumentation program based on guidelines in Agricultural Handbook 224 (Brakensiek et al. 1979). However, this reference is not all inclusive and adaptations have had to be made to local conditions.

Dr. Kenneth G. Renard (personal communication 1993) also noted several trends that may adversely affect the ARS Experimental Watershed program. First, there are very few persons hired who are truly instrumentation oriented experimentalists. Second, many locations have not been stressing data collection and processing experience for new hires as they have in the past. The current system of evaluation of ARS scientists may have contributed to this trend. In contrast, in the late 1950's and 1960's L.M. Glymph insisted every ARS scientist involved in the hydrology program would be involved in instrumentation and data collection. Most of the hydrology researchers of that era spent at least a year and sometimes several years of their initial careers based on the watersheds. In a UNESCO (1983) report on experimental experience in water resources education the necessity of experimentation for theoretical understanding is stressed. The report further states that "the gathering of data should be a well organized activity with a great deal of responsibility involved." These points should not be lost in future experimental watershed efforts or on future ARS scientists.

Methods of Analysis and Improvement

Modernization of all ARS experimental watershed by installing electronic datalogging equipment is a obvious way to improve the existing data collection program. Many of the experimental watersheds have or are already in the process of making this conversion. Conversion to datalogging equipment has its own inherent difficulties and 100 percent data capture is not guaranteed with this equipment. High speed INTERNET connections between experimental watershed research groups will serve several purposes in improving capabilities. Expertise in using new datalogging equipment and new instrumentation can and should be shared in a ARS Watershed E-mail bulletin board. High speed connections will facilitate large data transfers required to conduct inter-watershed data analysis and comparisons.

Research Opportunities

> *"The successful research person is the one who asks the right questions. Research must go on primarily in the mind and only secondarily in the physical and biological world."*
> *Leopold (1970)*

The existing ARS Experimental Watershed database, as well as the watershed instrumentation and support infrastructure afford unparalleled research opportunities. To fully grasp these opportunities, national, not individual location, objectives for the experimental watershed program must be set. The authors feel that a significant impact on the hydrologic sciences could be made if several national projects could be defined to conduct unified analyses of the entire ARS watershed network. But, as the statement by Leopold (1970) above points out, we must give thoughtful consideration of the research resources of the experimental watershed network and ask the right questions. The following questions are posed to help define significant research opportunities.

1. Can existing data from the nested watersheds present in many of ARS watershed locations be utilized to define the dominant hydrologic processes as a function of basin scale and perform inter-basin scale analyses across the major climatic regions represented by the watersheds? If the dominant or controlling processes can be defined as a function of basin scale and climatic region, both the data collection and modeling efforts can be focused and associated and economies be realized.

2. By conducting a unified time series, and spatial correlation analysis of rainfall-runoff data in the existing ARS database for all watersheds can:

    a. Long trends that may be the result of anthropogenic change be identified?

    b. Insight into the duration/cycles of floods and drought be acquired?

c. Design criteria to enhance water supply and minimize flood damage for local agricultural and engineering planning communities be improved?

d. Guidance and assistance be provided to agriculture to help it survive on the urban fringe where large cities may have altered the hydrologic regime?

3. Can the ARS further the science of land-atmosphere water and energy interactions by coupling hydrologic, energy, and atmospheric boundary layer measurements (including remote sensing), and by conducting interdisciplinary field campaigns over a variety of ARS Experimental Watersheds (such as MACHYDRO '90 over Mahantango, MONSOON '90 over Walnut Gulch, and the 1992 campaign over the L. Washita)? Conducting such experiments will facilitate and require interagency cooperation and offers an excellent opportunity to expand to larger watershed areas and to develop methodologies for aggregation and disaggregation across plot to watershed to basins scales (to 10^5 km^2).

4. Can the ARS quantify and predict the magnitude of groundwater/surface water interactions with existing and new measurements in experimental watersheds in both influent and exfluent channels (losing and gaining streams)?

5. Can small scale, economical measurement techniques be developed to obtain large area representative estimates with associated variability estimates? In many current model applications, variable and parameter estimates are derived from data collected at one scale and are misapplied in the model as representative for a much larger scale. In addition, concepts to measure sediment transport and concentration are 40-50 years old. Can new concepts and associated measurement instrumentation be developed or can we adapt new emerging technologies developed by other to local watershed conditions?

6. Can experimental watershed data and facilities be used to verify important water quality mitigation strategies such as filter strips, riparian reclamation, and constructed wetlands for water detention and cleansing in cooperation with SCS, EPA, and USGS? From a national perspective, how much uniformity in data collection is needed to test hypotheses, mitigation strategies and models? This is important as many regulatory agencies want methodology that applies nation-wide versus regionally.

In addressing any of the above research opportunities it is also important to quantify the uncertainty associated with measurements and predictions. To enable risk assessments to be incorporated into analyses it is necessary to have the ability to put confidence bounds around projections.

Conclusions

The ARS experimental watershed network was developed on the backs of many outstanding and dedicated scientists and technicians. Their vision, dedication, and associated research have resulted in many pivotal contributions to agricultural sustainability and hydrologic science. This group deserves special thanks for the treasure they have endowed to the future ARS Experimental Watershed Program. With this treasure comes commensurate responsibility to sustain and improve this program. Given the current and projected fiscal climate, efforts must be re-double to utilize the network to its fullest extent and fully integrate it into research efforts. The ability must be maintained to strike a balance between long term data collection and flexibility to meet new program needs. Research goals must be broadened from a location or individual watershed perspective to a national network perspective. A great deal will be gained by an integrated, national analysis of data from the experimental network. However, the ability to ask the right questions will be a paramount factor in gaining the utmost benefit from the ARS Experimental Watersheds. Kelly and Glymph (1965) recognized this fact early in planning ARS experimental watershed research in the temptation to try to solve all problems. This may not be realistic as instrumentation to study one set of objectives may be far different than required for another set of objectives. "The point emphasized here is that careful and thoughtful planning should precede initiation of studies on experimental watersheds. Careful consideration should be given to limiting the objectives of research to those for which resources are available - this on the theory that it is better to do a few things well than many things badly" (Kelly and Glymph 1965). Good advice from wise predecessors that all should heed.

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Table 1. Characteristics of Active ARS Watersheds (based on Jan. 1, 1991 figures, from DeCoursey (1992).

Size		Length of Record		Primary Land Use	
Hectares	No.	Years	No.	Type	No.
< 4	58	< 10	20	Crop	30
4 - 40	28	10 - 20	30	Pasture/Range	59
40 - 405	20	20 - 30	42	Mixed	46
405 - 4050	19	> 30	48	Meadow	1
> 4050	15			Pasture/Meadow	3
				Woodland	1

Table 2: Critical Measurement and Information Gaps in the ARS Experimental Watershed Network

Measurement or Information Gap	Related Auxiliary Meas./Information
Energy/radiation balance measurements	Direct evapotranspiration estimates
Basic suite of water quality/erosion Meas.	Long term at the field and watershed scale
GIS database coverages in easily accessible format	Topography, soils (including hydraulic properties), land cover, stream networks, basin boundaries and instrument locations, impoundments, geology and stratigraphy
Remotely sensed measurements over a variety of scales	Multi-spectral data at ground, aircraft and satellite altitudes
Distributed ecological/biomass Meas.	Microbial activity with depth
Biogeochemical balance measurements	Primary nutrients and evolution of greenhouse gases
Distributed, internal water, energy and sediment flux measurements	Required to verify distributed models
Paleo measurements to correlate and identify long term trends	Tree ring analysis, cosmogenic soil dating, etc.
Historical and descriptive Information (Metadata)	Track and document land use and instrumentation changes with assessments of

Figure 1. Location of active and closed ARS watersheds as of Jan. 1, 1992